CP-violating MSSM Higgs at Tevatron and LHC

Siba Prasad Das[1] **and Manuel Drees**[2]

[1] AHEP Group, Institut de Física Corpuscular – C.S.I.C./Universitat de València
Edificio Institutos de Paterna, Apt 22085, E–46071 Valencia, Spain,
[2] Bethe Center for Theoretical Physics and Physikalisches Institut, Universität Bonn,
Nussallee 12, D–53115 Bonn, Germany

E-mail: `spdas@ific.uv.es, drees@th.physik.uni-bonn.de`

Abstract.
   We analyze the prospect for observing the intermediate neutral Higgs boson (h_2) in its decay to two lighter Higgs bosons (h_1) at the presently operating hadron colliders in the framework of the CP violating MSSM using the PYTHIA event generator. We consider the lepton+ 4-jets+ $\not{E}_T$ channel from associate Wh_2 production, with $Wh_2 \to Wh_1h_1 \to \ell\nu_\ell b\bar{b}b\bar{b}$. We require two or three tagged b-jets. We explicitly consider all relevant Standard Model backgrounds, treating c-jets separately from light flavor and gluon jets and allowing for mistagging. We find that it is very hard to observe this signature at the Tevatron, even with 20 fb^{-1} of data, in the LEP–allowed region of parameter space due to the small signal efficiency. At the LHC, a priori huge SM backgrounds can be suppressed by applying judiciously chosen kinematical selections. After all cuts, we are left with a signal cross section of around 0.5 fb, and a signal to background ratio between 1.2 and 2.9. According to our analysis this Higgs signal should be viable at the LHC in the vicinity of present LEP exclusion once 20 to 50 fb^{-1} of data have been accumulated at $\sqrt{s} = 14$ TeV.

1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) [1] requires two Higgs doublets, leading to a total of five physical Higgs bosons. At the tree level, these can be classified as two neutral CP–even bosons (ϕ_1 and ϕ_2), one neutral CP–odd boson (a) and two charged bosons. In the presence of CP violation, the three neutral Higgs bosons can mix radiatively [2, 3]. The mass eigenstates h_1, h_2 and h_3 with $m_{h_1} < m_{h_2} < m_{h_3}$ can then be obtained from the interaction eigenstates ϕ_1, ϕ_2 and a with the help of the orthogonal matrix $O_{\alpha i}$, $(\phi_1, \phi_2, a)^T_\alpha = O_{\alpha i}(h_1, h_2, h_3)^T_i$, which diagonalizes the Higgs boson mass matrix. O depends on various parameters of the SUSY Lagrangian.

   Due to this mixing, the Higgs mass eigenstates are no longer CP eigenstates. Moreover, the masses of the Higgs bosons, their couplings to SM and MSSM particles, and their decays are significantly modified [3]. For example, the Higgs boson couplings to pairs of gauge bosons are scaled by g_{h_iVV} relative to the SM. These couplings can be expressed as $g_{h_iVV} = \cos\beta\, O_{\phi_1 i} + \sin\beta\, O_{\phi_2 i}$, where $\tan\beta$ is the ratio of Higgs vacuum expectation values (VEVs). The magnitude of g_{h_2WW} is directly related to the production process studied in this paper.

   In the absence of mixing between neutral CP–even and CP–odd states the LEP experiments were able to derive absolute lower bounds of about 90 GeV on the masses of both the lighter

CP–even Higgs and the CP–odd boson [4]. However, in the presence of CP violation, the LEP experiment were not able to exclude certain scenarios with very light h_1. In this "LEP hole" h_1 is dominantly a CP–odd state with almost vanishing coupling to the Z boson. One then has to search for Zh_2 or h_1h_2 production. In part of the LEP hole, these cross sections are suppressed by the rather large h_2 mass. Moreover, $h_2 \rightarrow h_1h_1$ decays lead to quite complicated final states, which often yield low efficiencies after cuts. One LEP–allowed region has m_{h_1} less than 10 GeV, so that $h_1 \rightarrow \tau^+\tau^-$ is dominant; in the other, $m_{h_1} \sim 30 - 50$ GeV so that $h_1 \rightarrow b\bar{b}$ is dominant. m_{h_2} lies between slightly below 90 and slightly above 130 GeV. Scenarios with even lighter h_2 are excluded by decay–independent searches for Zh_2 production [4]. If m_{h_2} is much above 130 GeV, the CP–odd component of h_1 becomes subdominant, so that the cross section for Zh_1 production becomes too large. Finally, the LEP hole occurs for $\tan\beta$ in between 3 and 10 [4]. We analyze the prospect for observing a signal for the production of neutral Higgs bosons in the second of these LEP allowed regions.

2. Numerical analysis

In our analysis we took five different benchmark points, denoted by S1 through S5 [m_{h_2}=130-90 GeV with m_{h_1}=30 GeV] and two CPX$_{0.5}$–scenario [CPX–1(2) where m_{h_2}=102 (103) GeV with m_{h_1}=36 (45) GeV, which can be realized for $M_{H^+} = 131.8$ GeV with $\tan\beta = 4.02$ (4.39)] of the MSSM [5]. We calculated the spectrum and the couplings for these two benchmark points using `CPsuperH` [3]. In our simulation we used the `PYTHIA v6.408` [6] event generator with the `SLHA` [7] interfacing option. We used `MadGraph/MadEvent v4.2.8` [8] for generating parton level SM backgrounds which were fed to `PYTHIA` for showering. We set the renormalization and factorization scale to $Q = \sqrt{\hat{s}}$ and used CTEQ5L for the parton distribution functions (PDF).

The signal arises from $p\bar{p} \rightarrow Wh_2 \rightarrow \ell\nu_\ell h_1h_1 \rightarrow \ell\nu_\ell b\bar{b}b\bar{b}$, leading to $\ell jjjj\not{E}_T$ events, where $\ell = e$ or μ. The effective cross section for this signal topology can be expressed as,

$$\sigma_{\text{signal}}^{\text{tot}} = \sigma_{SM}(p\bar{p}/pp \rightarrow Wh_2) \times g_{h_2WW}^2 \times Br(h_2 \rightarrow h_1h_1) \times Br(h_1 \rightarrow b\bar{b})^2 \times 2Br(W \rightarrow e\nu_e) , \quad (1)$$

where g_{h_2WW} is the h_2WW coupling in units of the corresponding SM value, W stands for $W^{\pm}$ and the factor 2 is for $\ell = $ e and μ. This process has recently been studied in refs.[9, 10], using parton–level analyses with quite promising results. We instead performed a full hadron–level analysis, including initial and final state showering as well as the underlying event. We take $g_{h_2WW}^2 \times Br(h_2 \rightarrow h_1h_1) \times Br(h_1 \rightarrow b\bar{b})^2 = 0.50$.

We simulate our signal and backgrounds at Tevatron Run-II with $\sqrt{s} = 1.96$ TeV. We have used the toy calorimeter simulation (`PYCELL`) provided in `PYTHIA` with the following criteria: calorimeter coverage is $|\eta| < 3.64$; the segmentation is given by $\Delta\eta \times \Delta\phi$=0.16 × 0.098 which resembles the CDF detector [11]; Gaussian smearing of the total energy of jets and leptons; a cone algorithm with $\Delta R(j,j) = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ has been used for jet finding; $E_{T,\text{min}}^{\text{cell}} \geq 1.5$ GeV is considered to be a potential candidate for jet initiator; minimum summed $E_{T,\text{min}}^{\text{jet}} \geq 10.0$ GeV is accepted as a jet and the jets are ordered in E_T; leptons ($\ell = $ e, μ) are selected with $E_T^\ell \geq 15.0$ GeV and $|\eta^\ell| \leq 2.0$ and no jet should match with a hard lepton in the event. We reconstructed the missing energy ($\not{E}_T$) from all observed particles.

The tagging of $b-$jets plays a crucial role in our analysis. A jet with $|\eta_j| \leq 1.2$ and $E_T^j \geq 15$ GeV "matched" with a $b-$flavored hadron ($B-$hadron), i.e. with $\Delta R(j, B - \text{hadron}) < 0.2$, is considered to be "taggable". We assume that such jets are actually tagged with with probability $\epsilon_b = 0.50$ [12]. We find that our tagging algorithm agrees well with the $t\bar{t}$ analysis of CDF [13]. We also modeled mistagging of non$-b$ jets as $b-$jets, treating $c-$jets differently from those due to gluons or light quarks with $\epsilon_c = 0.10$ and $\epsilon_{u,d,s,g} = 0.01$.

The cross-sections for the signal benchmarks lie in between $0.045 - 0.16$ pb while the total background is approximately 455 pb. We have displayed the raw number of events for signal
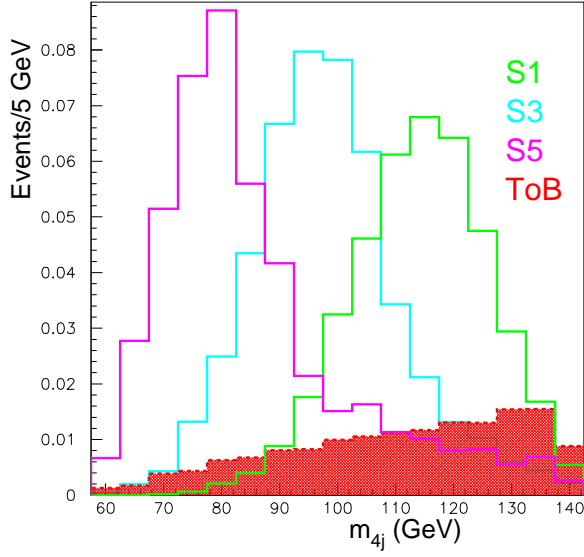
Figure 1. The four–jet invariant mass m_{4j} distribution after all cuts for signal scenarios S1, S3 and S5 and for the total background (ToB), requiring triple b−tag following the last column of Table 1 at Tevatron.
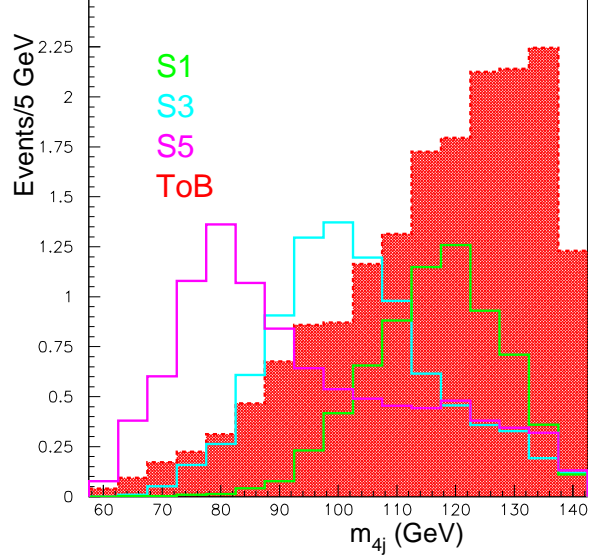
Figure 2. The four–jet invariant mass m_{4j} distribution after all cuts for signal scenarios S1, S3 and S5 and for the total background (ToB), requiring triple b−tag following the last column of Table 1 at LHC.

and backgrounds in the first column in Table 1. The second column is the number of events after applying the following basic acceptance cuts: $N_{\text{jet}} \geq 4$, $E_T^{j=1-4} > 10$ GeV, $|\eta^{j=1-4}| < 3.0$; $N_{\text{lepton}} \geq 1$, $E_T^{\ell} > 15$ GeV, $|\eta^{\ell}| < 2.0$ and $\not{E}_T \geq 15$ GeV. Not surprisingly, $t\bar{t}$ is the main source of background at this stage. We found that the suppressions by applying $N_{b-tag} \geq 2$ are almost the same for signal and $t\bar{t}$. The signal contains more b quarks, but the $t\bar{t}$ background has much harder b jets, leading to larger tagging probabilities. However, this background can contain a third b jet only due to showering. Hence requiring $N_{b-tag} \geq 3$ greatly reduces the background and increases the signal–to–background ratio. Unfortunately the small triple b−tagging probability, which lies between 1.3 and 3.6% depending on m_{h_2}, also reduces the signal rate.

We have also looked for invariant mass peaks to isolate the signal on top of a sizable background. In addition to the basic acceptance cuts (defined above) we demand that the signal contains exactly (rather than at least) four jets. This reduces combinatorial backgrounds for Higgs mass reconstructions. Finally, we pick the jet pairing $(ij)(kl)$ (with $i, j, k, l \in \{1, 2, 3, 4\}$) that minimizes the difference $m_{j_i j_j} - m_{j_k j_l}$ of di–jet invariant masses; in the absence of showering and for perfect energy resolution, the signal would have $m_{j_i j_j} = m_{j_k j_l} = m_{h_1}$. We then demand that both $m_{j_i j_j}$ and $m_{j_k j_l}$ lie between 10 and 60 GeV, where the lower bound comes from the requirement that $h_1 \rightarrow b\bar{b}$ decays should be allowed, and the upper bound from the requirement that $h_2 \rightarrow h_1 h_1$ decays should be open. We next require the four–jet invariant mass to lie between 60 and 140 GeV; this covers the entire "LEP hole" in the MSSM Higgs parameter space. Table 1 shows that after these cuts, the signal actually exceeds the total background.

The results of the column labeled Eff3 in Table 1 have been obtained by including all events that pass the other cuts (not related to tagging) and have at least three *taggable* jets, assigning each event a weight given by its (mis)tagging probability. This greatly increases the statistics. We checked that this gives results that are consistent with the event rejection technique whenever the latter has good statistics; this is the case if at most one b−tag results from mistagging.

The distribution of m_{4j} is shown in Fig. 1 for signal scenarios S1, S3 and S5 as well as for the

Table 1. Process column shows the signal benchmarks and the SM backgrounds, where j stands for u, d, s, g and – for background process 7 and 8 – c. RawEvt is stands for the number of events produced in the experiments (for backgrounds we applied basic pre–selections in the generator level: $p_T^{j,b} \geq 5$ GeV, $|\eta^{j,b}|<5.0$ and $\Delta R(jj, bb, bj) \geq 0.3$). N_{acc} is the number after the basic selection cuts, whereas N_{3b} is with at least three jets tagged as $b-$jets, allowing for mistagging. Eff3 is the number of events passing the selection cuts that contain exactly four jets and at least $3b-$ tagged jets; the numbers in parentheses represent the number of events with the inclusion of m_{pair} and m_{4j} cuts. Finally, ToB is the total number of background events.

	Tevatron with 4fb^{-1}				LHC with 10fb^{-1}			
Process	RawEvt	N_{acc}	N_{3b}	Eff3 (+h1)	RawEvt	N_{acc}	N_{3b}	Eff3(+h1)
S1	38.11	11.09	0.77	0.49 (0.40)	1157	352.5	33.48	13.96(6.85)
S2	51.59	13.85	0.83	0.51 (0.44)	1486	418.3	36.84	15.36(7.76)
S3	68.91	16.58	0.83	0.54 (0.47)	1962	506.5	39.81	17.03(8.91)
S4	94.76	19.88	0.87	0.54 (0.46)	2620	610.6	43.18	17.81(9.61)
S5	133.6	23.92	0.86	0.52 (0.45)	3516	724.7	43.92	18.96(9.63)
CPX-1	89.89	20.27	0.82	0.49 (0.43)	2509	600.2	40.07	17.25(9.07)
CPX-2	87.56	22.46	0.84	0.53 (0.47)	2421	597.2	40.28	16.88(9.64)
$t\bar{t}$	6760	3545	25.62	9.65(0.05)	1,690,000	818,800	7795	1469(5.52)
$b\bar{b}b\bar{b}W^{\pm}$	12.59	1.52	0.06	0.03(0.01)	337.6	31.8	4.10	2.95(0.53)
$b\bar{b}bjW^{\pm}$	0.043	0.01	0	0(0)	23.3	2.3	0.13	0.11(0.01)
$b\bar{b}cjW^{-}$	131.2	17.6	0.05	0.02(0.01)	73,170	7359	77.56	56.50(6.79)
$b\bar{b}c\bar{c}W^{\pm}$	44.51	5.53	0.03	0.01(0.01)	1126	89.9	1.68	1.17(0.25)
$b\bar{b}jjW^{\pm}$	5181	610.2	0.28	0.15(0.06)	535,700	45,830	17.14	17.89(1.93)
$bjjjW^{\pm}$	14.31	2.01	0	0(0)	7194	586.3	0.23	0.05(0.01)
$jjjjW^{\pm}$	384000	47340	0.24	0.02(0)	59,700,000	4,332,000	2.18	4.59(0.68)
$t\bar{t}b\bar{b}$	12.15	6.80	0.44	0.03(0)	10,100	5700	751.5	72.82(1.28)
$t\bar{t}c\bar{c}$	21.69	13.66	0.19	0.02(0)	16,440	9245	259.8	31.54(0.45)
ToB	396200	51550	26.91	9.93(0.14)	62,030,000	5,220,000	8910	1657(17.45)

total background. We observe clear peaks for the signal, which are shifted downwards due to, for example, showering (by 10 to 15 GeV) from the naive expectation $m_{4j} = m_{h_2}$ at the parton level.

By seeing the distributions of m_{pair} (average of the two optimal pairing of di–jet invariant masses) and m_{4j} (see Fig. 1) allow us define the final significance of the signal by counting events that satisfy: $0.6m_{h_1} \leq m_{\mathrm{pair}} \leq m_{h_1} + 5$ GeV and $0.7m_{h_2} \leq m_{4j} \leq m_{h_2} + 10$ GeV. We see that requiring triple $b-$tags leads to very good signal to background ratio, of around 10 for $m_{h_1} = 30$ GeV and slightly less for heavier h_1. However, we expect less than 2 signal events after all cuts for a total integrated luminosity ($\int \mathcal{L}dt$) of 20 fb^{-1}. We tried also to see the effect for two $b-$tag and found that the signal rate increase by a factor between 3.7 and 5 while the background increases by two orders of magnitude and $S/\sqrt{B}$ is well below two.

The significance defined in this way overestimates the true statistical significance of a double peak in the m_{pair} and m_{4j} distributions somewhat, due to the "look elsewhere" effect: since m_{h_1} and m_{h_2} are not known a priori, one would need to try different combinations when looking for peaks. However, given that we use rather broad search windows, there are probably only $\mathcal{O}(10)$ statistically independent combinations within the limits of the LEP hole. Note also that the

signal rate is still quite small. Further kinematical cuts, which might slightly increase the signal to background ratio, are therefore not likely to increase the statistical significance of the signal. We are therefore forced to conclude that the search for $Wh_2 \to Wh_1h_1 \to \ell\nu b\bar{b}b\bar{b}$ events at the Tevatron does not seem promising, and turn instead to the LHC.

Our analysis for the LHC follows broadly similar lines as that for the Tevatron. We simulate our signal and backgrounds at the LHC with $\sqrt{s} = 14$ TeV. The PYCELL model is based on the ATLAS detector [14] with calorimeter coverage $|\eta| < 5.0$, segmentation $\Delta\eta \times \Delta\phi = 0.087 \times 0.10$. We use a Gaussian energy resolution for leptons and jets and a cone algorithm for jet finding, with $\Delta R(j,j) = 0.4$. Calorimeter cells with $E_{T,min}^{cell} \geq 1.0$ GeV are considered to be a potential candidates for jet initiator. All cells with $E_{T,min}^{cell} \geq 0.1$ GeV are treated as part of the would–be jet; minimum summed $E_{T,min}^{jet} \geq 15.0$ GeV is accepted as a jet and the jets are ordered in E_T; leptons ($\ell = $ e, μ) are selected if they satisfy $E_T^\ell \geq 20$ GeV and $|\eta^\ell| \leq 2.5$. The jet–lepton isolation criterion and the missing transverse energy $\not{E}_T$ are adopted similar to our Tevatron analysis.

Only jets with $|\eta_j| < 2.5$ are considered to be taggable as $b-$jets. If the jet is "matched" to a $b-$flavored hadron, with $\Delta R(j, \text{hadron}) \leq 0.2$, the tagging efficiency is taken to be 50%. If instead the jet is matched to a $c-$hadron, the (mis)tagging efficiency is taken to be 10%, whereas jets matched to a $\tau-$lepton have zero tagging probability. All other taggable jets have (mis)tagging probability of 0.25%. These efficiencies follow recent ATLAS analyses [15, 16, 17].

The cross-sections for the signal benchmarks lie between $0.5 - 1.7$ pb while the total backgrounds is approximately $2.84 \cdot 10^4$ pb. We have displayed the raw number of events for signal and backgrounds (again with the same generator–level cuts as of Tevatron) in the first column in Table 1. The second column is the number of events after applying the basic acceptance cuts: $N_{jet} \geq 4$, $E_T^{j=1-4} > 15$ GeV, $|\eta^{j=1-4}| < 5.0$; $N_{lepton} \geq 1$, $E_T^\ell > 20$ GeV $|\eta^\ell| < 2.5$ and $\not{E}_T \geq 20$ GeV. They reduce the cross section by about a factor of 5 (3) for $m_{h_2} = 90$ (130) GeV.

The number of events (for $\int \mathcal{L}dt = 10$ fb^{-1}) passing the acceptance cuts and containing exactly four jets, at least three of which are tagged (adopting the same strategy like Tevatron), is given by the Eff3 column of Table 1. Similar to Tevatron we require both jet pair invariant masses to lie between 10 and 60 GeV and m_{4j} to lie between 60 and 140 GeV. The m_{4j} distribution is shown in Fig. 2. After these cuts we are left with slightly less than one signal event and slightly less than two background events per fb^{-1} of data. A 5σ signal would then require almost 100 fb^{-1} of data, more than the LHC is likely to collect during "low" luminosity running.

We also checked that requiring a fourth $b-$tag reduces the signal cross section by another order of magnitude or more. The signal rate then becomes so low that one would have to wait for the high–luminosity phase of the LHC to accumulate enough events to reconstruct invariant mass peaks. We therefore stick to triple $b-$tag in our LHC analysis.

We found that the background shows a peak in the m_{pair} distribution between 30 and 40 GeV, not far from the peak of the signal in the scenarios we consider. A tighter cut on m_{pair} will nevertheless improve the signal–to–background ratio. Moreover, the four–jet invariant mass distribution (in Fig. 2) of the background peaks at large values, largely due to the contribution from $t\bar{t}$ production. At least for scenarios with h_2 masses in the lower half of the "LEP hole" region a tighter cut on m_{4j} will therefore also improve the significance of the signal. We therefore applied the same "double–peak" cuts as at the Tevatron. The signal then always exceeds the background. Assuming an integrated luminosity of 60 fb^{-1} at the end of "low" luminosity running, we find a final statistical significance of at least 5 standard deviations, and a signal sample of some 30 events.

3. Conclusions

We analyzed the possibility of observing neutral Higgs bosons at currently operating hadron colliders in the framework of the CP violating MSSM. We explored the $\ell jjjj\not{E}_T$ channel with double, triple and quadruple b tag, focusing on the region of parameter space not excluded by LEP searches. We considered a large number of SM backgrounds and employed a full hadron–level Monte Carlo simulation using the PYTHIA event generator. We carefully implemented $b-$tagging, including mistagging of $c-$jets or light flavor or gluon jets. At the Tevatron, requiring $3b-$tag, we can only expect about one signal event per 10 fb^{-1} of $\int \mathcal{L}dt$, on a background of about 0.3 events. If we require only $2b-$tag, the signal increases by a factor of about 4, but the background increases by two orders of magnitude, making the signal unobservable. At the LHC we focussed on events with exactly four jets, cutting simultaneously on the average di–jet invariant mass and the four–jet invariant mass and demanding at least $3b$-tags. We found a signal rate above the background, and a signal significance exceeding 5σ for an $\int \mathcal{L}dt$ of 60 fb^{-1}. One might be able to increase the S:B ratio even more by requiring $4b-$tags with softer tagging criteria (enhancing mistag rate also), possibly simultaneously relaxing the requirement on the number of jets. This could be used to confirm the existence of a signal.

We conclude that searches for Wh_2 production at the LHC with $W \to \ell\nu$ and $h_2 \to h_1 h_1 \to b\bar{b}b\bar{b}$ should be able to close that part of the "LEP hole" in parameter space where $h_1 \to b\bar{b}$ decays dominate. The details of this analysis can be found in our recent paper [18].

3.1. Acknowledgments

References

[1] For introductions into supersymmetric extensions of the Standard Model in general, and the MSSM in particular, see e.g. M. Drees, R.M. Godbole and P. Roy, *Theory and Phenomenology of Sparticles*, World Scientific, Singapore (2004); H.A. Baer and X.R. Tata, *Supersymmetry: from superfields to scattering events*, Cambridge Press (2006).

[2] A. Pilaftsis, Phys. Rev. **D58** (1998) 096010; Phys. Lett. **B435** (1998) 88; E. Accomando *et al.*, arXiv:hep-ph/0608079.

[3] J.S. Lee *et al.*, Comput. Phys. Commun. **156** (2004) 283; Comput. Phys. Commun. **180**, 312 (2009).

[4] S. Schael *et al.* (ADLO Collab.) Eur. Phys. J. C **47** (2006) 547; OPAL Collab., G. Abbiendi *et al.*, Eur. Phys. J. **C27** (2003) 311; DELPHI Collab., J. Abdallah et al., Eur. Phys. J. **C38** (2004) 1; P. Bechtle *et al.*, Comput. Phys. Commun. **181** (2010) 138.

[5] M. Carena, J.R. Ellis, A. Pilaftsis and C.E.M. Wagner, Phys. Lett. B **495** (2000) 155, hep-ph/0009212.

[6] T. Sjostrand, S. Mrenna and P. Skands, JHEP **0605**, 026 (2006).

[7] P. Skands *et al.*, JHEP **0407**, 036 (2004).

[8] F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003).

[9] K. Cheung, J. Song and Q.-S. Yan, Phys. Rev. Lett. **99** (2007) 031801, hep-ph/0703149.

[10] M. Carena, T. Han, G.Y. Huang and C.E.M. Wagner, JHEP **0804**, 092 (2008), arXiv:0712.2466 [hep-ph].

[11] **CDF** Collab., T. Aaltonen *et al.*, *Phys. Rev. Lett.* **100** (2008) 091803; **CDF IIb** Collab., P. T. Lukens, *The CDF IIb detector: Technical design report*, FERMILAB-TM-2198.

[12] K. Hanagaki [D0 Collab.], FERMILAB-CONF-05-647-E; C. Neu [CDF Collab.], FERMILAB-CONF-06-162-E; T. Wright [CDF and D0 Collabs.], arXiv:0707.1712 [hep-ex]; M.T. Bowen *et al.*, Phys. Rev. D **72**, 074016 (2005).

[13] D. Acosta *et al.*, Phys. Rev. D **71** (2005) 052003.

[14] The Atlas Collab., CERN-LHCC-99-15, ATLAS-TDR-15 (1999).

[15] G. Aad *et al.* [The ATLAS Collab.], arXiv:0901.0512 [hep-ex].

[16] M. Lehmacher, arXiv:0809.4896 [hep-ex].

[17] E. Alagoez *et al.*, Particle Physics with CMS for the LHC, http://unizh.web.cern.ch/unizh/Activities/cms.htm.

[18] S. P. Das and M. Drees, to appear.